Starbursts from strong compression of galactic molecular clouds due to the high pressure of the intracluster medium

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ABSTRACT

We demonstrate that the high pressure of the hot intracluster medium (ICM) can trigger the collapse of molecular clouds in a spiral galaxy, leading to a burst of star formation in the clouds. Our hydrodynamical simulations show that the high gaseous (ram pressure and static thermal) pressure of the ICM strongly compresses a self-gravitating gas cloud within a short time scale ($\sim 10^7$ yr), dramatically increasing the central gas density, and consequently causing efficient star formation within the cloud. The stars developed in the cloud form a compact, gravitationally bound, star cluster. The star formation efficiency within such a cloud is found to depend on the temperature and the density of the ICM and the relative velocity of the galaxy with respect to it. Based on these results, we discuss the origin of starburst/poststarburst populations observed in distant clusters, the enhancement of star formation for galaxies in merging clusters, and the isolated compact HII regions recently discovered in the Virgo cluster.

Subject headings: galaxies: clusters: general — galaxies: ISM — galaxies: interaction — galaxies: star clusters

1. Introduction

Recent spectrophotometric and morphological studies of cluster galaxies by large ground–based telescopes and the *Hubble Space Telescope* (*HST*) have revealed that the star formation histories are very different between different morphological and luminosity classes and can be closely associated with galactic morphological evolution driven by cluster-related physical processes (e.g., Lavery & Henry 1994; Couch et al. 1994, 1998; Abraham et al. 1996; Balogh et al 1999; Dressler et al. 1999). For example, Couch et al. (2001) revealed that star formation of disk galaxies in distant clusters are globally and uniformly suppressed. Poggianti et al. (1999) found that galaxies with "e(b)" spectral type,

which are the most likely to be starbursting galaxies, generally belong to the low-luminosity dwarf populations in clusters. It has been a longstanding and remarkable problem what mechanisms are responsible for the observed enhancement/decline of galactic star formation rates in clusters.

The dynamical and hydrodynamical effects of the hot, high-temperature ICM have long been suggested to play decisive roles, not only in transforming galactic morphological properties but also in controlling star formation rates in galaxies within clusters (e.g., Gunn & Gott 1972; Gavazzi & Jafffe 1985; Bothun& Dressler 1986; Evrard 1991). Fujita & Nagashima (1999) demonstrated that star formation rates and photometric properties of galaxies in clusters can be changed as a result of the ram pressure effects on galactic molecular clouds. Using three dimensional SPH/N-body simulations, Abadi et al. (1999) found that although the ram pressure of the ICM can efficiently strip interstellar HI gas from spirals, such ram pressure stripping alone can not abruptly truncate star formation in spirals. However, these previous phenomenological/numerical models have not investigated the effects of the ICM on *individual molecular clouds with internal structures, kinematics, and chemical abundance*, even though star formation is ongoing within individual molecular clouds. Therefore, it is still unclear how the star formation rate and efficiency in individual galactic molecular clouds is influenced by the hot ICM (and thus how the galactic star formation can be controlled by the ICM).

The purpose of this *Letter* is to first demonstrate that the high gaseous pressure of the ICM significantly changes the internal structure of a self-gravitating molecular gas cloud in a cluster disk galaxy and consequently trigger a burst of star formation within the cloud. In particular, we investigate (1) the star formation caused within gas clouds in a disk galaxy due to the strong compression of the gas by the ICM, and (2) its dependence on the density and the temperature of the ICM and the velocity of the galaxy relative to the ICM. We show that both ram pressure and static pressure from the ICM on the galactic gas clouds are important in compressing the clouds and thus in triggering starbursts within the clouds. We emphasize that although the ICM can be responsible for the stripping of *HI gas within disks* and *diffuse halo gas* in cluster galaxies and thus for the truncation of star formation (e.g., Abadi et al. 1999; Bekki et al. 2002), it could also be closely associated with starburst activity in cluster/group environments. Finally, this proposed new mechanism for triggering starbursts is discussed in a variety of different contexts of cluster galaxy evolution.

2. Our Model

By using TREESPH code with star formation methods (Bekki 1997), we numerically investigate the hydrodynamical effects of the ICM on a self-gravitating molecular gas cloud orbiting within a spiral galaxy under the gravitational influence of the galaxy and its surrounding dark matter halo. The cloud is represented by 20,000 SPH particles and the initial cloud mass ($M_{\rm cl}$) and size ($r_{\rm cl}$) are set to be $10^6\,M_{\odot}$ and 97 pc, respectively, which are consistent with the mass-size relation observed by Larson (1981). The cloud is assumed to have an isothermal radial density profile with $\rho(r) \propto 1/(r+a)^2$, where a is the core radius of the cloud and set to be $0.2 r_{\rm cl}$. An isothermal equation of state with a sound speed of $c_{\rm s}$ is used for the gas, and $c_{\rm s}$ is set to be $4\,{\rm km\,s^{-1}}$ (consistent with the prediction from the virial theorem) for models with $M_{\rm cl} = 10^6\,M_{\odot}$.

Each SPH particle is subject to the gravitational forces from the fixed spiral potential that is assumed to have three components: a dark matter halo, a disk, and a bulge. We assume a logarithmic dark matter halo potential ($\Phi_{\rm halo} = v_{\rm halo}^2 \ln(r^2+d^2)$), a Miyamoto-Nagai (1975) disk ($\Phi_{\rm disk} = -GM_{\rm disk}/\sqrt{R^2+(a+\sqrt{z^2+b^2})^2}$), and a spherical Hernquist (1990) bulge ($\Phi_{\rm bulge} = -GM_{\rm bulge}/(r+c)$), where r is the distance from the center of the spiral, $d = 12\,{\rm kpc}$, $v_{\rm halo} = 131.5\,{\rm km\ s^{-1}}$, $M_{\rm disk} = 10^{11}\ M_{\odot}$, $a = 6.5\,{\rm kpc}$, $b = 0.26\,{\rm kpc}$, $M_{\rm bulge} = 3.4 \times 10^{10}\ M_{\odot}$, and $c = 0.7\,{\rm kpc}$. This set of parameters is reasonable and realistic for the Galaxy. The cloud is initially within the disk plane (corresponding to the x-y plane) and located at (x, y, z) = (R_g, 0, 0). The initial velocity of the cloud is set to be ($v_{\rm x}$, $v_{\rm y}$, $v_{\rm z}$) = (0, $v_{\rm c}$, 0), where $v_{\rm c}$ is the circular velocity at the position. We show the results for $R_g = 8.5\,{\rm kpc}$ (corresponding to the solar neighborhood) in this paper, because we find that the star formation within clouds does not depend strongly on R_g.

Each SPH particle is also subject to the hydrodynamical force of the ICM whose strength depends on the parameters of the ICM. The ICM is represented by 8,824 SPH particles and and an isothermal equation of state with temperature, T (or sound velocity of $c_{\rm h}$), and density, ρ. The cloud – which is in a spiral that orbits the cluster core with a velocity, $V_{\rm rel}$, relative to the ICM – is subject to both ram pressure ($P_{\rm ram} \propto \rho {V_{\rm rel}}^2$) and thermal static pressure ($P_{\rm s} \propto \rho {c_{\rm h}}^2$). The ICM particles are uniformly distributed in an annular ring with size $R_{\rm g}$, width $6R_{\rm cl}$, and thickness $6R_{\rm cl}$ (in the z direction) on the disk. We give all ICM particles an initial velocity of (0, $V_{\rm rel}$, 0), so that we can represent the hydrodynamical effects that the ICM has on the spiral when it passes through the cluster core. Periodic boundary conditions are adopted only for these ICM particles. We here stress that for the adopted total number of SPH particles ($\sim$30000), the simulations can not fully resolve the contact surface between the cold GMC and the hot ICM (accordingly thermal conduction between these gas and the cloud evaporation can not be fully investigated). The

star formation rate in our simulations can be therefore overestimated (as discussed later in this paper).

A gas particle in a cloud is converted into a collisionless stellar particle if (1) the local dynamical time scale [corresponding to $(4\pi G\rho_i)^{-0.5}$, where G and ρ_i are the gravitational constant and the density of the gas particle, respectively] is shorter than the sound crossing time (corresponding to $h_i/c_{\rm s}$, where h_i is the smoothing length of the gas), and (2) the gaseous flow is converging. This method thus mimics star formation due to Jeans instability in gas clouds. In the model without ICM effects, star formation does not occur at all in this star formation method. By changing the values of the three parameters (i.e., T, ρ, and $V_{\rm rel}$), we investigate the effects of the ICM on the cloud. We show the results for the models with $0.01T_0 \le T \le T_0$, with $0.1\rho_0 \le \rho \le \rho_0$, and $0.1V_0 \le V_{\rm rel} \le V_0$, where T_0, ρ_0, and V_0 are 8 keV, 5.6×10^{-27} g cm^{-3}, and 1000 km s^{-1}. These values of T_0 and ρ_0 correspond to the observed values of the ICM in the central region of the Coma cluster (Briel et al. 1992). We mainly show the result of the "fiducial model" with $T = T_0$, $\rho = 0.1\rho_0$, and $V_{\rm rel} = 1000$ km s^{-1}, because this model shows the typical behavior of ICM-induced star formation in a gas cloud. The gas cloud can not be suddenly stripped because of the higher initial column density during simulations (See also Fujita & Nagashima 1999).

3. Results

Figures 1 and 2 describe how a burst of star formation within a gas cloud can be triggered by the external gas pressure of the ICM in the fiducial model. In this model with moderately strong ram pressure, the high pressure of the ICM can continue to strongly compress the cloud without losing a significant amount of gas from the cloud (i.e., only 3% of the initial mass can be stripped within 14 Myr). As the strong compression proceeds, the internal density/pressure of the cloud can rise significantly. However, the self-gravitational force of the cloud also becomes stronger because the cloud becomes progressively more compact during the ICM's compression. Therefore, the internal gaseous pressure of the cloud alone becomes unable to support itself against the combined effect of the external pressure from the ICM and the stronger self-gravitational force. As a result of this, the cloud's collapse initially induced by the high external pressure from the ICM can continue in a runaway manner.

Due to the rapid, dissipative collapse, the gaseous density of the cloud dramatically rises and consequently star formation begins in the central regions of the cloud. The star formation rate increase significantly from 0.1 $M_{\odot}$ yr^{-1} (for the first 5 Myr) to 0.6 $M_{\odot}$ yr^{-1} (8 Myr after the start of the cloud's collapse). This corresponds to global galactic

star formation rate of $30-60\ M_\odot\ \mathrm{yr}^{-1}$ for galaxies with total H_2 mass similar to that of the Galaxy. About 81% of the gas is converted into stars within 14 Myr to form a stellar system. Because of the "implosive" formation of stars from strongly compressed gas, the developed stellar system is strongly self-gravitating and compact. This result implies that high external pressure from the ICM is likely to trigger the formation of bound, compact star clusters rather than unbound, diffuse field stars.

Parameter dependences are found to be complicated and can be summarized as follows (see Figure 3): Firstly, for the high ICM temperature ($T = T_0$), large relative velocity ($V_{\mathrm{rel}} = V_0$) models, the star formation efficiency (hereafter SFE) within a cloud is higher for the model with the lower ICM density (ρ). This is because in the higher ρ model, the ram pressure of ICM strips a larger amount of gas from the cloud and thus decreases the total amount of gas that can be converted into stars. Secondly, for the models with lower ρ ($= 0.1\rho_0$) and lower T ($= 0.1T_0$), the SFE is higher for the model with the larger V_{rel}. This suggests that the moderately strong ram pressure of the ICM can play a role in enhancing the star formation rate in a gas cloud. Thirdly, for models in which ram pressure has a negligible effect on the gas cloud (i.e, high density, $\rho = \rho_0$, and very low ICM relative velocity, $V_{\mathrm{rel}} = 0.01V_0$), the SFE is likely to be higher for the model with higher T. This is because the higher static (thermal, external) pressure of the ICM in the model with higher T can more strongly compress a cloud and thus produce regions of high gaseous density within. Fourthly, for models in which ram pressure is very strong ($\rho = \rho_0$ and $V_{\mathrm{rel}} = V_0$), there is no clear dependence on T.

4. Discussion and conclusions

By assuming that galactic molecular clouds can be exposed to the hot ICM, we have demonstrated that the high pressure from the ICM can trigger efficient star formation in gas clouds in cluster spirals. However, the diffuse outer halo gas and the disk HI gas of a cluster spiral could prevent the molecular gas clouds from being directly exposed to the hot ICM. Using semianalytic models of galaxy formation, Okamoto & Nagashima (2003) demonstrated that molecular gas clouds can be consumed up by star formation in cluster spirals before the ram pressure effects become significant for their evolution. Furthermore, evaporation of gas clouds by heat conduction (Cowie & McKee 1977) could reduce significantly the gas mass that can be converted into stars, because the time scale of cloud evaporation is an order of $10^6 - 10^8$ years for the adopted parameters of gas clouds in the present study. For the adopted cloud parameters, the fraction of gas that can be evaporated before star formation within the gas can be estimated as 12 %. Therefore, the

proposed ICM-induced starbursts in molecular gas clouds may be more likely for galaxies which only have small amounts of HI and halo gas yet have enough molecular gas. In spite of this strong limitation in the applicability of the proposed mechanism to the starburst phenomenon within clusters, we suggest that the present results may still have the following three important implications for cluster galaxy evolution.

The first is that if the ICM triggers a starburst in a disk galaxy rich in molecular gas, actively star-forming regions can be widely spread throughout the disk. The expected distribution of starburst regions within a disk is in striking contrast to the nuclear starbursts suggested to be triggered by tidal interactions/mergers between galaxies and global cluster tidal fields (e.g., Byrd & Valtonen 1990). Furthermore, the starburst mechanism proposed here for cluster disk galaxies differs from that for mergers in that the thin disk component remains intact after the starburst in the former whereas it is destroyed to form a thick disk in the latter (e.g., Bekki 1998). Therefore, *widely spread starburst (or poststarburst) activity within the thin disk component* of a cluster disk galaxy is the signature to look for in identifying this ICM-gas cloud interaction. Spectroscopic observations that can reveal the detailed distributions of starburst/poststarburst regions within a disk (e.g., the GMOS Integral Field Unit on the 8m Gemini telescope) will reveal such ICM-induced starburst/poststarburst populations in distant clusters.

The second is that a larger fraction of starburst/poststarburst populations are expected in merging clusters, where a higher ICM temperature (and pressure) is predicted (e.g., Roettiger et al. 1997). However, it is unclear (both observationally and theoretically) whether cluster merging triggers starbursts in cluster disk galaxies and what mechanisms are responsible for the formation of starburst galaxies in merging clusters. Although some observational evidence has been found for merging clusters having a larger number of starbursts/poststarburst candidates both at low (Caldwell et al. 1993; Caldwell & Rose 1997) and intermediate redshifts (e.g., Owen et al. 1999), Venturi et al. (2000) found no such clear evidence in the merging clusters Abell 2125 and 2645. Bekki (1999) demonstrated that the time-dependent tidal gravitational field of merging clusters can trigger starbursts in their galaxies whereas Fujita et al. (1999) concluded that ram pressure stripping can strongly suppress the star formation of galaxies in merging clusters. More extensive observational investigations of (1) a correlation between the fractional content of starburst/poststarburst galaxies and the incidence/non-incidence of cluster merging, and (2) the spatial distribution of starburst/poststarburst galaxies within merging clusters, will address the above two unresolved problems in a more quantitative way.

The third is that the origin of isolated intracluster compact HII regions recently discovered in the Virgo cluster (e.g., Yoshida et al. 2002; Arnaboldi et al. 2003; Gerhard et

al. 2003) can be closely associated with ICM-induced efficient star formation in gas clouds drifting in the cluster. The ICM-induced efficient star formation might be highly likely to be seen in the intracluster molecular gas clouds stripped from cluster spirals through interactions between them (and between them and the cluster global tidal fields), because these intracluster gas clouds are directly exposed to ICM. We suggest that the total number and spatial distribution of isolated intracluster HII regions in the Virgo cluster provide valuable information on the cluster's dynamical history of galaxy interaction/merging that have been responsible for stripping of molecular clouds within disks. Our results also imply that the formation of intracluster globular clusters (West et al. 1995) and planetary nebulae (Arnaboldi et al 1996) could result from the past interaction between stripped gas clouds and ICM.

The present results imply that some fraction of molecular clouds in cluster spirals could disappear from their disks, not by tidal or ram pressure stripping but by rapid consumption due to ICM-induced star formation. They also imply that the initial mass function (IMF) of a gas cloud with ICM-induced star formation could be different from the normal Salpeter-like IMF, because the ICM-induced star formation can occur preferentially in the central regions of gas clouds, where more massive stars are likely to be formed (e.g., Murray et al. 1996). Our future, more sophisticated simulations which will include chemical evolution, magnetic fields, dynamical evolution of hierarchical/fractal structures within a cloud, and feedback effects from massive stars and supernovae will address the total amount of molecular gas consumed by ICM-induced star formation and its IMF in a more quantitative way.

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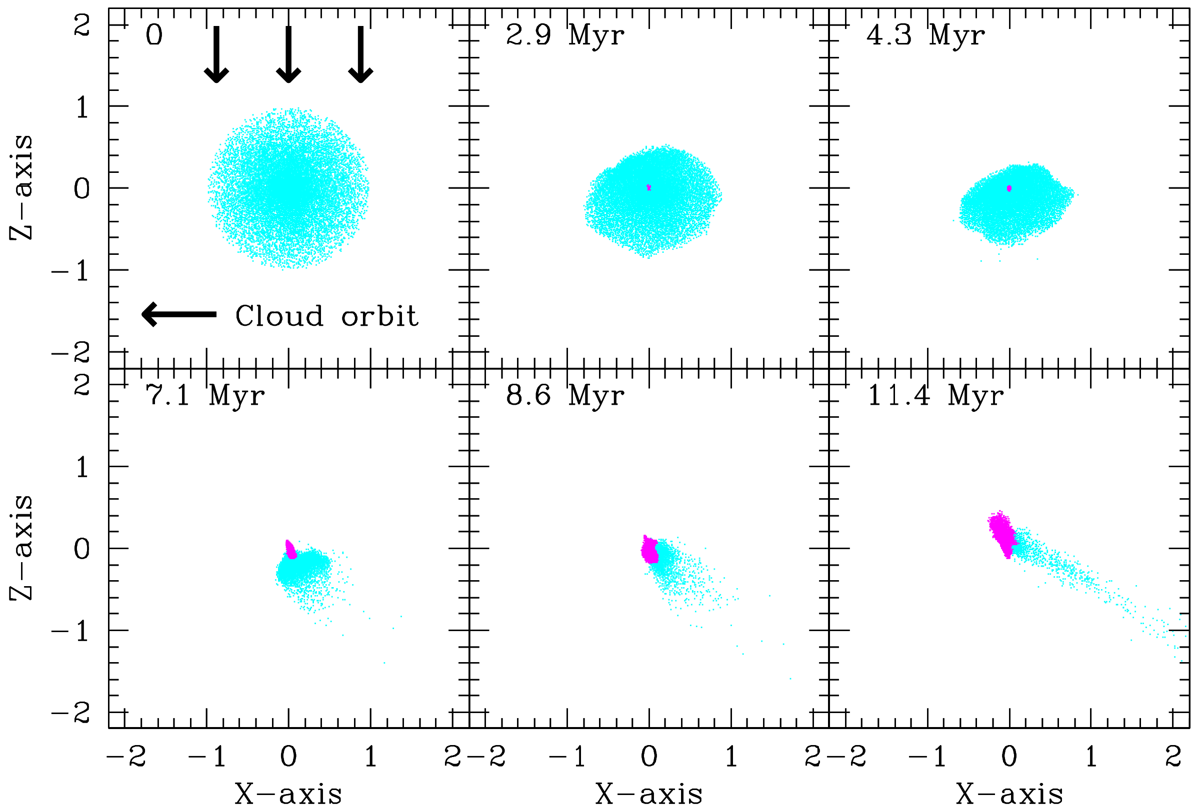
Fig. 1.— Distribution of gas (cyan) and new stars formed from gas (magenta) of the self-gravitating cloud projected onto the x-z plane for the fiducial model, at each time indicated in the upper left corner of each panel. The size is given in units of the cloud size (97 pc) so that each frame measures 423 pc on a side. the upper left corner of each panel. The upper three short arrows and the lower long arrow indicate the direction of the ICM flow with respect to the galactic motion and that of the cloud motion, respectively. The cloud is initially within the x-z plane plane and orbiting within the disk in a counter-clockwise. Note that owing to strong external compression by ICM, the gas cloud rapidly collapses to start star formation in its central region.

Fig. 2.— Time evolution of the star formation rate in units of $M_{\odot}$ yr^{-1} (upper) and that of the normalized gas mass (solid) and stellar mass (dotted). Here gaseous and stellar masses are normalized to initial gas mass.

Fig. 3.— Dependence of the mass fraction of new stars ($M_{\rm s}/M_{\rm g}$) within a cloud on model parameters: Dependences on ICM density (upper left), relative velocity between ICM and disk galaxies (upper right), and ICM temperature (lower left and right). $M_{\rm s}$ and $M_{\rm g}$ are the total mass of new stars formed within 14 Myr and initial gas mass of the clouds, respectively. In each panel, four models with different values of one of the three parameters (ρ, T, and $V_{\rm rel}$) and the fixed ones of the other two are plotted. The fixed parameter values of temperature, density, and relative velocity (represented by T, D, and V) are indicated in the upper right corner of each panel in units of T_0 (8 keV), ρ_0 (5.6×10^{-27} g cm^{-3}), and V_0 (1000 km s^{-1}), respectively. For example, the upper left panel shows the dependence of $M_{\rm s}/M_{\rm g}$ on ICM density for models with $T = 8$ keV, $V_{\rm rel} = 1000$ km s^{-1}, and $\rho = 0.1$, 0.25, 0.5, $1.0\rho_0$.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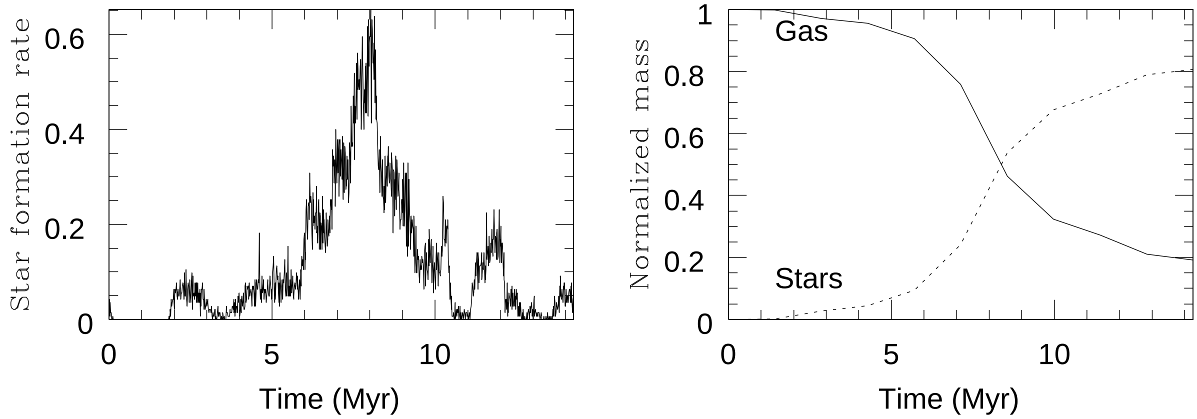
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10
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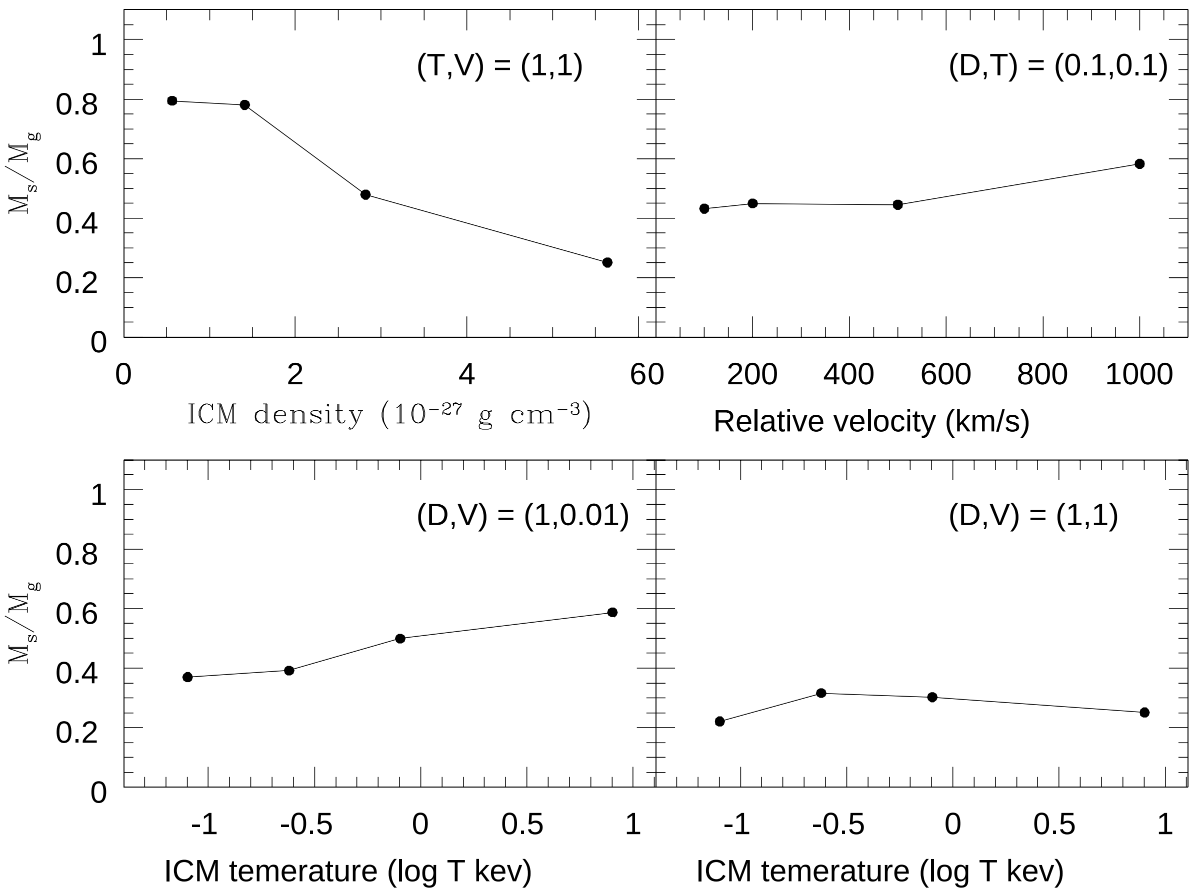
0.2
0
Gas
Stars
0
5
10
Time (Myr)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(D,T) = (0.1,0.1)
(D,V) = (1,0.01)
(D,V) = (1,1)
M_s/M_g
ICM density (10^{-27} g cm^{-3})
Relative velocity (km/s)
ICM temerature (log T kev)
ICM temerature (log T kev)
0
0.2
0.4
0.6
0.8
1
0
2
4
60
200
400
600
800
1000
-1
-0.5
0
0.5
1